Acoustic Techniques for Uncertainty Shallow Ocean Environments

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LONG-TERM GOALS

The overall long-term goal for this project is to develop engineering tools that are useful to the Navy as it operates in uncertain and/or unknown ocean environments. During the last year, this project has changed its emphasis from predicting the impact of environmental uncertainty on acoustic propagation calculations to determining the utility of a time-reversal-based technique for source tracking and identification in poorly known or unknown ocean waveguide environments. Thus, two sets of long-term goals are stated here.

The long term goals of this project up to the end of 2008 were: *i*) to quantitatively determine the uncertainties in underwater sound field predictions that arise from uncertainty in environmental parameters, *ii*) to compare the performance of different schemes for determining acoustic uncertainty, and *iii*) to determine how to exploit in-situ acoustic measurements and the generic propagation characteristics of underwater sound channels in order to enhance the performance of active and passive sonar systems in unknown or uncertain ocean environments.

The long term goals of this project since the beginning of 2009 are: *i*) to determine the effectiveness of artificial time reversal (ATR) for the purposes of blind deconvolution in noisy unknown ocean sound channels, *ii*) to effectively apply ATR to marine mammal sounds recorded in the ocean with vertical and/or horizontal arrays, and *iii*) to utilize the ATR-corrected signals and ocean-sound-channel impulse response estimates to identify and track individual marine mammals (or other sound sources of interest).

OBJECTIVES

Through the end of 2008, this project sought to quantitatively determine what can be predicted with underwater sound calculations for uncertain ocean environments. The capabilities of future Navy sonar systems will be enhanced if they can fully exploit modern calculation techniques for underwater sound propagation. Unfortunately, imperfect knowledge of an ocean environment causes sound propagation calculations to be inherently uncertain. However, the accuracy limits of sound propagation calculations with uncertain input parameters and boundary conditions are not readily determined from the calculation routines themselves. Thus, the objectives of this project were: *a*) to quantitatively predict the uncertainty in the acoustic amplitude in ocean acoustic propagation simulations that comes from uncertainty in the environmental parameters (water column depth and sound speed, bottom slope, bottom density and sound speed, etc.) used to specify the computational

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14. ABSTRACT

The overall long-term goal for this project is to develop engineering tools that are useful to the Navy as it operates in uncertain and/or unknown ocean environments. During the last year, this project has changed its emphasis from predicting the impact of environmental uncertainty on acoustic propagation calculations to determining the utility of a time-reversal-based technique for source tracking and identification in poorly known or unknown ocean waveguide environments. Thus, two sets of long-term goals are stated here.

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environment, and *b*) to quantitatively compare the performance of acoustic uncertainty predictions from: the field shifting approach developed as part of this research effort, the polynomial chaos technique developed at NRL, and direct-simulation and/or Monte-Carlo methods.

In 2009 this project has focused on developing an acoustic-ray-based version of artificial time reversal (ATR), a technique for recovering the original signal and the source-to-array impulse response for a remote unknown sound source in an unknown ocean waveguide [1]. The specific objectives are to *a*) determine the signal-to-noise, array size, and array element number limitations of ATR via acoustic propagation simulations, *b*) verify these findings with simple airborne-sound laboratory experiments involving up to eight microphones and several ray paths, *c*) obtain and process at-sea array recordings of remote-but-cooperative sound sources, and *d*) obtain and process marine mammal vocalizations for the purposes of marine mammal tracking and identification. This research effort will extend the past mode-based version of ATR [2] to higher frequencies and smaller receiving arrays, and will identify its capabilities and limitations.

APPROACH

Over the last year, this project has exploited analytical, computational, and experimental techniques in approximately equal portions. The formulation of ATR and the polynomial chaos (PC) uncertainty technique are primarily analytical. In particular, the PC work was an extension of the narrow-angle parabolic-equation ideal-waveguide PC solution [3]. Acoustic propagation calculations have been performed with the modal-sum propagation model (KRAKEN) for sound field calculations from 100 Hz to 2.5 kHz at ranges from 1 km to 10 km in sound channels having depths of 50 m to 200 m with depth-dependent sound speed. These propagation calculations have been used to develop an approximate technique for efficiently determining the probability density function (PDF) of acoustic amplitude, *A*, when one or more environmental parameters are uncertain and the PDFs of these uncertain parameters are known [4]. Since the beginning of 2009, a simple airborne-sound laboratory experiment has been under development. It will soon be used for testing and validation of ATR concepts, ideas, and implementation details. The acoustic uncertainty effort described in this report is completed the doctoral research of Kevin R. James. The ATR blind deconvolution portion of this research effort is the current doctoral research of Shima Hosseinabadi

WORK COMPLETED

As mentioned above, this project involved two somewhat separate efforts on environmental-uncertainty-induced acoustic uncertainty and blind deconvolution via ATR. The uncertainty work culminated with comparisons of the direct simulations, polynomial chaos, and field shifting methods at a realistic sound speed uncertainty level in the idealistic Pekeris waveguide. These comparisons involved 900 propagation scenarios covering 10 frequencies (100 Hz to 1 kHz), 10 source-receiver ranges (1 km to 10 km), three receiver depths (above, below and at mid water column), and three bottom types (sand, silt, and gravel) for sound speed uncertainties of 1 m/s to 20 m/s. Unfortunately, the PC technique is not yet sufficiently developed for more extensive tests with multiple uncertain variables.

The work completed as part of the blind deconvolution effort has involved developing broadband simulations of ray-based ATR from the KRAKEN modal sum code, and the design and construction of a simple and inexpensive airborne-sound laboratory experiment that will be used to refine the ATR technique before applying it to ocean-measured sound signals. The simulations will concentrate on signals in the few hundred Hz to few kHz range and short receiving arrays composed of four to sixteen

elements. The laboratory experiments will match these signal frequencies and will involve several ray paths that (at least partially) mimic ocean multipath propagation. Here, it must be mentioned that this is a new effort being performed by a new student, so final archival-quality results are not yet available. However, prior work on ray-based ATR has been written up and submitted for publication [1].

Figures 1 and 2 show samples of the current simulation work. Figure 1 presents the simulated signals for 16 receivers evenly spaced in depth in a 100-m-deep sound channel at a source-array range of 1 km. The source is at mid water column and its emitted signal is a Gaussian-weighted sine wave with a center frequency of 2 kHz. The bandwidth of the simulations extends from 1.5 kHz to 2.5 kHz. Here the diamond pattern arises from surface and bottom reflections in the sound channel and each receiver hears nine possibly-overlapping ray-path arrivals. The second figure shows the output of a simple plane-wave beamformer vs. the angle from the horizontal for a 14-m-long 8-element receiving array centered at a depth of 50 m in this sound channel. The nine beamformer peaks correspond to the nine wave-front arrivals (i.e. nine acoustic ray paths). These simulation results document essential steps for assessing and refining the performance of ATR before it is applied to at-sea array recordings, and are merely intended to show that this project is well underway.
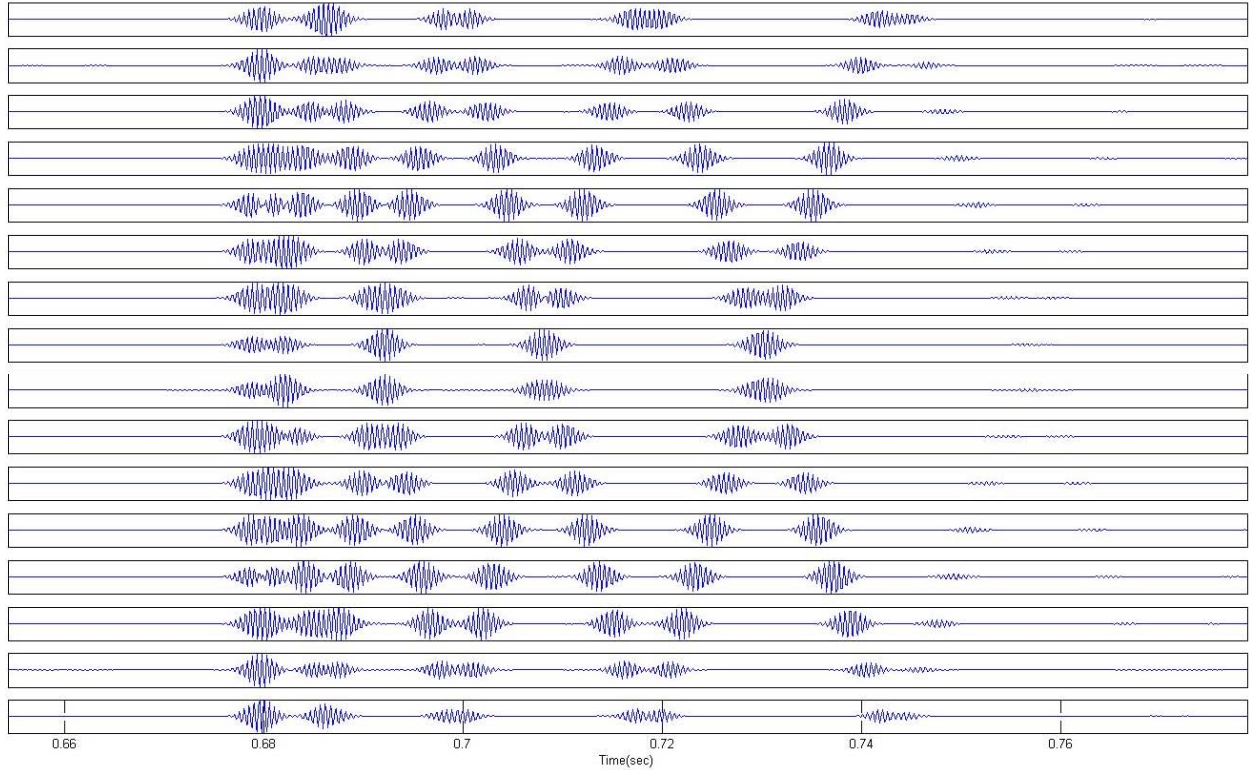

Figure 1. Simulated received signals for sixteen elements of a receiving array spread evenly through a 100-m-deep sound channel. The mid-water-column source, 1 km away, broadcast a single Gaussian-weighted sine wave pulse with a center frequency of 2 kHz and a nominal bandwidth of several hundred Hz. Each receiver hears eight or nine possibly overlapping signal replicas. In each case, the leading edge of the signal is the sound traveling on the direct ray path. The signal coda arises from surface and bottom reflections.
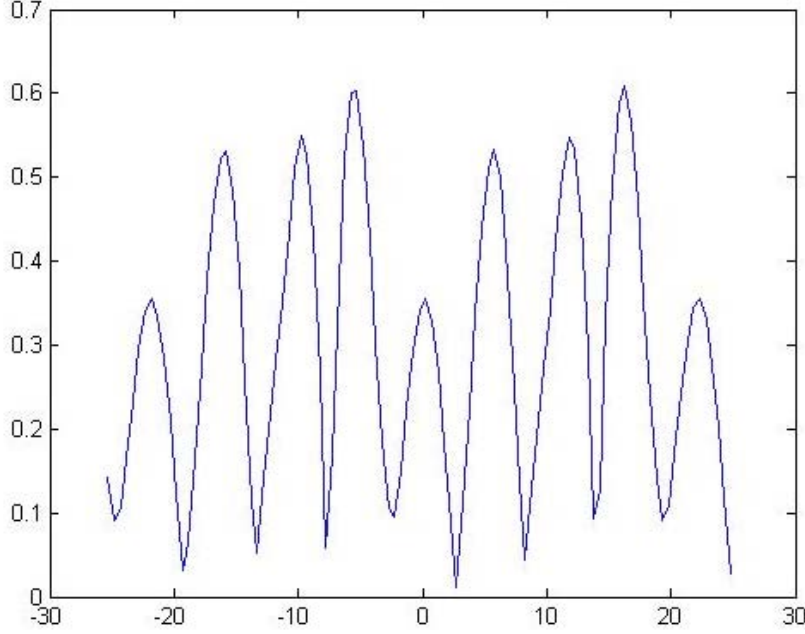
Figure 2. Plane wave beamformer output vs. angle from the horizontal for a 14-m-long 8-element receiving array centered at a depth of 50 m in the sound channel of Figure 1. The nine peaks correspond to the nine wavefronts (ray paths) seen at this depth in Fig. 1.

RESULTS

The final results for the Perkeris-waveguide comparisons of acoustic uncertainty predictions techniques are presented on Figure 3 for a relatively efficient implementation of the direct simulation technique (DS, 21 field calculations), the field shifting technique (FS, 2 field calculations), and the polynomial chaos technique (PC, truncation order = 21) for a Gaussian-distributed uncertain water-column sound speed having a mean of 1500 m/s and uncertainty of $\sigma_c = 1$ m/s to 20 m/s. For clarity, results from the various techniques are shifted slightly at each of the six values of σ_c. The vertical axis specifies the median accuracy and 95% confidence interval for each uncertainty assessment technique based on calculations from the 900 propagation scenarios mentioned above. Here accuracy is specified by an absolute difference error norm, L_1, between an approximate probability density function for acoustic amplitude $PDF_a(A)$ determined from the uncertainty assessment technique and a numerically-converged direct-simulation PDF determined from 401 field calculations, $PDF_{nc}(A)$,

$$L_1 = \int_o^\infty \left| PDF_a(A) - PDF_{nc}(A) \right| dA \ . \tag{1}$$

This error norm has a well-defined range, $0 \leq L_1 \leq 2$, with $L_1 = 0$ and 2 implying a perfect match and complete mismatch, respectively. Typically, $L_1 < 0.2$ produces a good visual match between $PDF_a(A)$ and $PDF_{nc}(A)$ while L_1 near or above unity implies a poor match. For the comparison in this figure, the field shifting technique's computational cost is approximately one order of magnitude less than that of the other techniques. Figure 3 shows that all three techniques loose accuracy as sound speed uncertainty increases in a Perkeris waveguide. However, all three techniques can be considered successful (median $L_1 < 0.2$) up to sound speed uncertainties of 10 m/s or so. The 21-field-calculation direct-simulation technique is the most reliable; the upper limit of its 95% confidence interval is the

4

lowest at each value of σ_c. Yet, the field shifting technique's accuracy shows less dependence on the input sound speed uncertainty than the other techniques and it provides the lowest median L_1 at the highest sound speed uncertainty, $\sigma_c = 20$ m/s. Here the polynomial chaos technique struggles at the higher values of σ_c because the its series truncation order was fixed at 21 to match the computational effort level of the 21-calculation DS technique; the truncation order was not optimized to produce the best PC results.
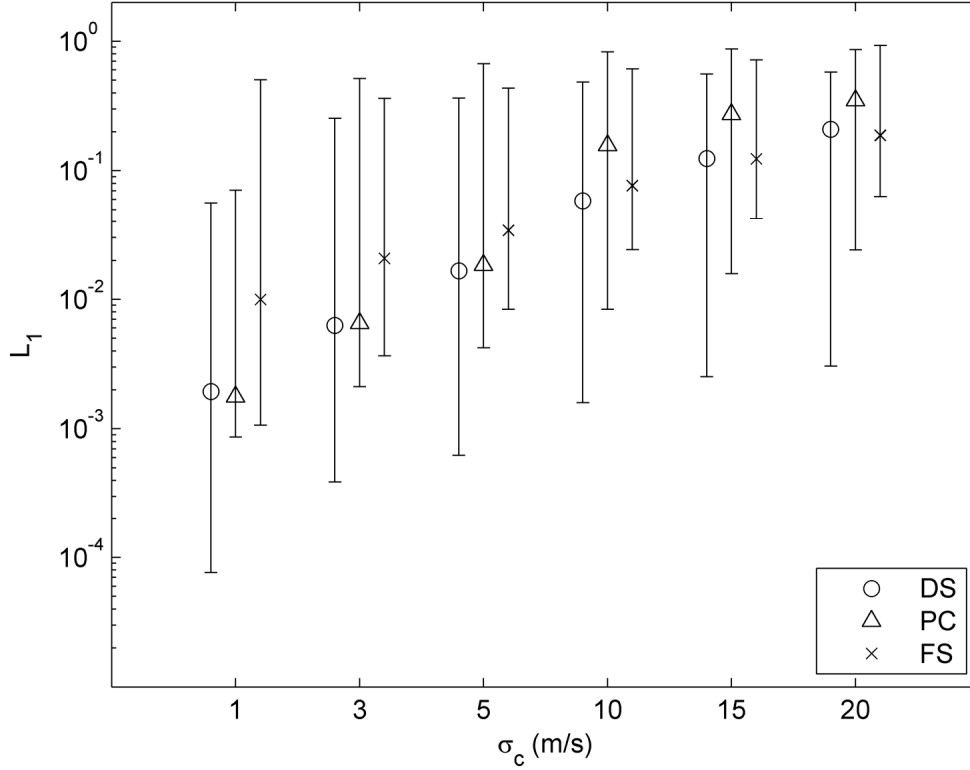

Figure 3. 95% confidence intervals and median absolute integrated errors, L_1, of the approximate probability density function (PDF) of acoustic amplitude (A) vs. sound-speed standard deviation, σ_c, in a Pekeris waveguide having a Gaussian-distributed uncertain water column speed of sound with a mean of 1500 m/s. The symbols mark the medians for each technique and the error bars span the 95% confidence interval for 900 propagation scenarios covering 10 frequencies (100 Hz to 1 kHz), 10 source-receiver ranges (1 km to 10 km), three receiver depths (above, below and at mid water column), and three bottom types (sand, silt, and gravel). The three acoustic uncertainty assessment techniques are 21-field-calculation direct simulations (DS), 2-field-calculation field shifting (FS), and polynomial chaos with a series truncation order of 21 (PC). Here, DS is the most reliable, while FS is the most accurate at high sound speed uncertainties.

IMPACT/APPLICATION

In broad terms, this project ultimately seeks to determine what is possible for a sonar system when the available environmental information is uncertain or even unknown. The capabilities of future Naval sonar systems will be enhanced: *i*) if acoustic propagation predictions and their uncertainty can be properly included in final results or in a tactical decision aid, and *ii*) when sonar techniques are developed that do not rely on detailed knowledge of the acoustic environment. Thus, this research

effort on quantifying predicted-field uncertainties and determining the effectiveness of ray-based artificial time reversal, a new blind deconvolution scheme, should eventually impact how transducer (array) measurements are processed for detection, localization, tracking, and identification.

TRANSITIONS

The results of the acoustic uncertainty portion of this effort should aid in the design of sonar signal processors for tactical decision aids, and in determining which features of an acoustic environment must be known accurately for effective sonar operations that involve use of acoustic field predictions. In particular, Dr. Lee Culver's ONR-funded REVEAL (Receiver Exploiting Variability in Estimated Acoustic Levels) sonar signal processing effort at Penn State ARL could benefit from the results of this investigation. In addition, the Navy's extensive large-scale ocean acoustic transmission-loss calculations as conducted by Drs. Josette Fabre and Robert Zingarelli at NRL Stennis might be simplified or reduced through the use of advanced or efficient uncertainty assessment techniques.

RELATED PROJECTS

Dr. Steve Finette's polynomial chaos program at NRL-DC is the research project that is most closely related to the acoustic uncertainty effort described here. In addition, ONR is also funding an on-going multi-investigator experimental effort on environmental and acoustic uncertainty that emphasizes oceanography. For the blind deconvolution effort, Dr. Aaron Thode of SIO has agreed to potentially work with us and provide at-sea marine mammal recordings once we are ready to analyze such recordings.

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HONORS AND AWARDS

Prof. Karim G. Sabra of the Georgia Institute of Technology who first formulated the ATR blind deconvolution technique with Prof. Dowling while at the University of Michigan won the 2008 A. B. Wood Medal and Prize of the Institute of Acoustics, UK. Prof. Dowling won the 2009 John F. Ullrick Education Excellence Award and the 2009 American Association of Engineering Education Outstanding Professor Award for the College of Engineering at the University of Michigan.